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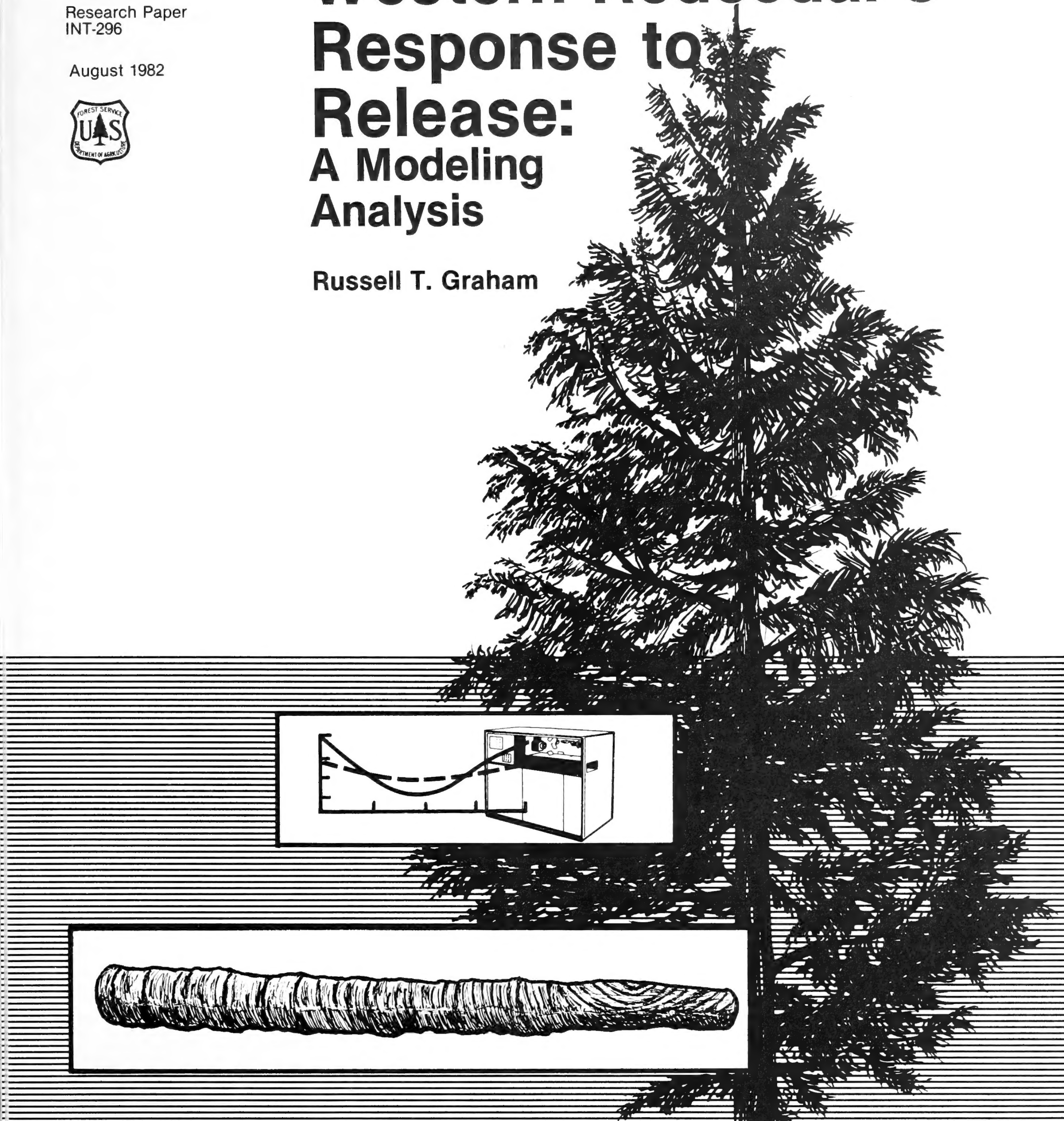
Influence of Tree and Site Factors On Western Redcedar's Response to Release:

A Modeling Analysis

Russell T. Graham



THE AUTHOR

RUSSELL T. GRAHAM is a research forester working in the silviculture of the cedar, hemlock, grand fir ecosystems project at the Forestry Sciences Laboratory, Moscow, Idaho. He began his career with the USDA Forest Service in 1973 as a forester on the Bitterroot National Forest and joined the Intermountain Station in 1975. He received his B.S. in forestry from the University of Montana and his M.S. and Ph.D. in forestry from the University of Idaho.

RESEARCH SUMMARY

Western redcedar is one of the most important commercial species in the Northern Rocky Mountains. The species usually responds well to release, but the response often varies tremendously, depending on site and tree characteristics. Therefore, this study was implemented to identify the site, stand, and tree characteristics associated with the release response of western redcedar. Because no untreated stands were available to compare to the treated stands, a diameter increment model was developed and used in the analysis.

Western redcedar appeared to best respond to release from overhead and surrounding competition on northerly aspects. In contrast, the poorest response to release occurred on southerly aspects. After release the species showed the best growth in the *Thuja plicata/Pachistima myrsinites* habitat type and the poorest growth on the *Tsuga heterophylla/Pachistima myrsinites* habitat type.

The larger the tree was at the time of release the better it responded to release. In contrast, the older the tree was at the time of release the poorer the response it had to the treatment.

Soil characteristics were also associated with the release response of western redcedar. Trees growing on soils with high pH's showed the poorest responses to release. Also, trees growing on soils with large amounts of total nitrogen, iron, and copper showed poorer responses to release, whereas soils with larger amounts of nitrate, ammonium, sulfate, and potassium supported the trees that showed the better growth rates after release.

In addition, foliage characteristics of western redcedar were associated with the diameter increment response of the species to release. Trees with the larger amounts of foliar phosphorus and manganese had better growth rates after release than trees with smaller amounts of these nutrients. Trees with larger amounts of foliar sulfur, iron, sodium, and potassium had poorer growth rates after release compared to trees with smaller amounts of these nutrients.

Foliage color was related to the response of western redcedar to release. Trees with green-yellow colored foliage showed a better response to release than trees with greenish green-yellow foliage. Also, foliage color indicated the nutrient content of the foliage; mean nutrient content differed among 12 different colors.

The results of this study show that western redcedar will respond favorably to release from overhead and surrounding competition. The site and tree characteristics that are related to the release response may be used to help design treatment alternatives for releasing stands of western redcedar.

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INTRODUCTION

Western redcedar (*Thuja plicata* Donn.), occupying approximately 330,000 acres (133 500 hectares), with a total live volume of 10 billion board feet (Bolsinger 1979), is one of the more important commercial species in the Northern Rocky Mountains. The natural durability and good wood working properties of western redcedar make it desirable for use by the building industry. Because of its natural resistance to decay, western redcedar is ideally suited for use as posts, poles, shakes, shingles, and for siding. In recent years the demand for split products and lumber has caused large price increases for western redcedar. In western Washington and northwestern Oregon, western redcedar log prices increased from $57.30 per thousand board feet in 1965 to $320.80 per thousand board feet in 1977 (Bolsinger 1979) and continued to show an increase in current markets. Of the estimated 950 million board feet of western redcedar harvested between 1975 and 1976, 66 percent consisted of trees that were 21 inches (53.3 cm) diameter at breast height and larger (Bolsinger 1979).

Western redcedar in the Northern Rocky Mountains grows on many different sites where it occurs as a climax or accidental species on five different habitat types (Daubenmire and Daubenmire 1968; Steele and others 1976). Western redcedar is the major climax species on the *Thuja plicata/Pachistima myrsinites*, *Thuja plicata/Athyrium filix-foemina*, and *Thuja plicata/Oplopanax horridium* habitat types. On the *Tsuga heterophyla/Pachistima myrsinites* habitat type, western redcedar is a minor climax species; it is an accidental species on the *Abies lasiocarpa/Pachistima myrsinites* habitat type.

Western redcedar usually grows in association with other tree species, such as western white pine (*Pinus monticola* Dougl. ex. D. Don), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), western larch (*Larix occidentalis* Nutt.), grand fir (*Abies grandis* [Dougl.] Lindl.), ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), and lodgepole pine (*Pinus contorta* Dougl.). Western redcedar is one of the most shade-tolerant species growing in the cedar-hemlock ecosystems of the Northern Rocky Mountains. It is capable of reproducing and becoming established under the shade of faster growing seral species. The prolific nature of its seed production often leads to regeneration of thousands of seedlings per acre, creating dense, overstocked, slow-growing stands.

Northern Idaho, eastern Washington, and western Montana have large forested acreage in which western redcedar is a major component of the understory. Because western redcedar is shade tolerant, these understory trees may be multiaged and diverse in size. The question of how to manage these stands using practices such as overstory removal, cleaning, weeding, or thinning is becoming increasingly relevant. Therefore, the objectives of this study were to identify the tree, site, and stand characteristics that were associated with the diameter increment responses of western redcedar to release from overhead and surrounding competition.

THE SITE, STAND, AND TREE CHARACTERISTICS ASSOCIATED WITH THE RELEASE RESPONSE OF WESTERN REDCEDAR

Literature Review

Growth of shade-tolerant tree species increases in response to the removal of overhead and surrounding competition. Overstory removal has been found effective in increasing growth rates of shade-tolerant coniferous understory species (Leaphart and Foiles 1972; Koenigs 1969; Ferguson and Adams 1979; Seidel 1977). Likewise, understories of tolerant deciduous trees can be released successfully (Johnson 1975; Carvell 1967; Sander and others 1976). Growth response after overstory removal is often delayed one or more years as the understory becomes acclimated to its new environment (Herring 1977; Herring and Ethridge 1976). Shade-tolerant species are also capable of increased growth rates after intermediate stand treatments such as cleanings and thinnings (Deitschman and Pfister 1973; Berry 1968).

Tree characteristics such as diameter, height, crown condition, rooting habit, and age are related to the growth performance of a tree after release. Larger diameter tolerant trees usually show better growth response after release than smaller diameter trees (Leaphart and Foiles 1972; Herring and Ethridge 1976; Johnson 1975). Shade-tolerant trees with extensive symmetrical root systems and little root mortality respond well to release (Leaphart and Grismer 1974; Eis 1974). The response of tolerant species to release is related to tree age in some species such as grand fir (*Abies grandis* [Dougl.] Lindl.) (Ferguson and Adams 1979); however, age is not associated with the response of other species such as subalpine fir (*Abies lasiocarpa* [Hook.] Nutt) (Herring 1977, Crossley 1976).

Site characteristics are important in governing the amount of growth that occurs after a tolerant species is released. Most tolerant coniferous species respond best to release from competition on cool, moist sites (Ferguson and Adams 1979; Herring 1977; Herring and Ethridge 1976), as do many deciduous trees (Johnson 1975).

Release cuttings can increase the chance of disease in the residual trees. When the overstory was removed and the residual western redcedar stand thinned in a northern Idaho site, 69 percent of the trees were infected by root rotting organisms, while in the untreated stand only 36 percent of the trees were infected (Koenigs 1969). Similarly, Berry (1968) reported high mortality caused by root diseases in thinned stands of white spruce (*Picea glauca* [Moench] Voss). Release cuttings in stands of western hemlock can increase root diseases by damaging residual trees thus providing entry points for disease causing organisms, and also by creating stumps that can be colonized by root pathogens (Wallis and Morrison 1975).

The leaves of shade-tolerant species are adapted to low light conditions and must change or be replaced when exposed to increased light. Shade-tolerant beech (*Fagus grandifolia* Ehrh.) leaves are efficient in dim light with leaf stomata opening rapidly in response to low light levels (Woods and Turner 1971). This allows the species to take advantage of short periods of light for photosynthesis even though the photosynthetic rate may be very low (Loach 1967). In addition, tolerant species have low respiration rates that help them survive in shaded conditions (Loach 1967). Trees with leaves adapted to shaded environments often die or develop parch blight when suddenly exposed to open light conditions (Boyce 1961). The death or damage of trees released from competition can be related to the inability of the foliage to adapt or change to the new light conditions. Depending upon the amount of exposure, many shade leaves on a tree will drop when a release cutting occurs, as others adapt to the new light conditions (Tucker and Emmingham 1977). Leaves developing on released shade-grown trees usually have two rows of palisade mesophyll cells compared to one row on the shade-grown leaves (Aussenac 1973). Shade-grown leaves that do not drop will often increase in thickness and in weight-to-length ratios, thus becoming more adapted to their new environment (Tucker and Emmingham 1977).

Methods

DATA COLLECTION

A survey approach was used to study the response of western redcedar diameter growth at breast height (d.b.h.), to various kinds of release from competition, including thinning, weeding, cleaning, and overstory removal. To assure that a response could be measured, stands chosen for sampling had a minimum of 10 years of tree growth since the release treatment. Each stand selected was uniform in slope, aspect, soil type, and stand history. Fifteen stands meeting the selection criteria were located on various ownerships in eastern Washington, northern Idaho, and western Montana during the summer of 1979. No western redcedar stands examined in the central portion of the study area satisfied the stand selection requirements (fig. 1).

Selected stands were described as follows: geographic location, habitat type (Daubenmire and Daubenmire 1968), elevation above sea level, slope, slope configuration, aspect, and year of release treatment. The habitat types represented by the stands in the study include: *Thuja plicata/Pachistima myrsinites* (THPL/PAMY), *Thuja plicata/Athyrium filix-foemina* (THPL/ATFI), *Tsuga heterophylla/Pachistima myrsinites* (TSHE/PAMY), and *Abies lasiocarpa/Pachistima myrsinites* (ABLE/PAMY).

Within each of the 15 stands, two 5-point clusters were established for sampling the trees and lesser vegetation. Each point was the center of a 1/300-acre (0.00133-ha) fixed-radius plot for measurements of trees up to 5 inches (12.7 cm) d.b.h. and a variable-radius plot for measurements of trees 5 inches (12.7 cm) d.b.h. and larger. A basal area factor was used that resulted in selection of four to six trees in the variable radius plot. For each tree the following were recorded: species, crown class, d.b.h., height, crown ratio (live crown as

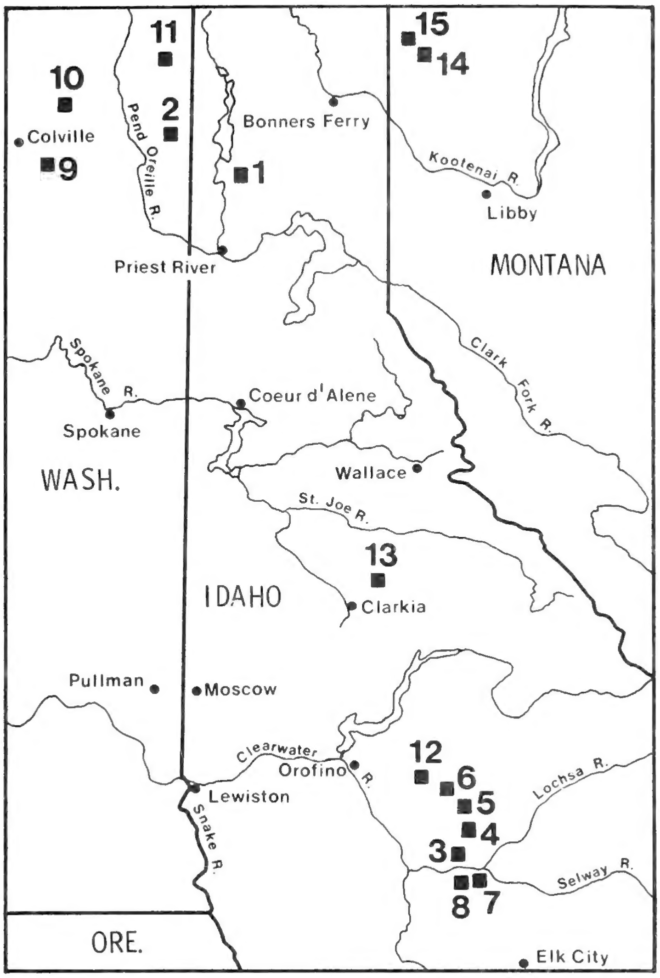

Figure 1.—Stands used to investigate the growth response of western redcedar to release from competition.

percentage of tree height), and descriptions of any visible damage or injury. From each tree on the variable-radius plots, one increment core to the tree center was extracted at breast height (b.h.) from the side facing the plot center. On each fixed-area plot, the proportion covered by crowns of each shrub species was estimated to the nearest 10 percent and the heights of shrubs were measured to the nearest 1 foot (30.5 cm). Using an occular system developed by Wellner (1979), the percentage of sunlight striking the forest floor was estimated within each stand.

DATA PREPARATION

The 15 stands had a wide variety of characteristics. Mean stand diameters were small, ranging from 0.8 inches (2.0 cm) to 3.0 inches (7.6 cm), and densities varied from 1,296 to 49,289 trees per acre (3,202 to 121,796 per ha) (table 1). The smallest and largest mean stand d.b.h.'s for the 601 growth-sample trees measured on the variable-radius plots, were 6.5 inches (16.5 cm) and 31.8 inches (80.8 cm), respectively (table 2).

Thirty variables, both observed and derived, for the 601 growth-sample trees were included in the data as follows:

1. Stand location — geographic location on USGS quadrangle maps
2. Habitat type — (Daubenmire and Daubenmire 1968)
3. Stand elevation — 100's of feet measured by an altimeter
4. Slope configuration — ridge top, upper slope, mid-slope, lower slope, valley bottom
5. Aspect azimuth — degrees
6. Slope angle — percent
7. Year of release — date
8. Shrub height by species — feet
9. Shrub cover by species — percent of forest floor covered by shrub crowns on 1/300-acre (0.0013-ha) plot
10. Sunlight striking forest floor — percent (Wellner 1979)
11. Tree species — (Little 1979)
12. Tree diameter at breast height — nearest 0.1 inch using diameter tape
13. Tree height — nearest 1.0 foot, using clinometer
14. Crown ratio — percentage of tree height in live crown
15. Crown class — (Smith 1962)
16. Description of damage or injury to the tree
17. Tree age at breast height based on count of annual growth rings
18. Annual tree ring widths — millimeters
19. Diameter inside bark for various growth periods computed from annual growth ring measurements (d.i.b.)
20. Basal area percentile — position of tree in stand basal area distribution (BAP)
21. Basal area of larger trees computed from tree list (BAL)
22. Stand crown competition factor (CCF) (Krajicek and others 1961)
23. Stand trees per acre (TPA)
24. Stand basal area (BA) per acre
25. Cluster crown competition factor (CCF)
26. Cluster trees per acre (TPA)
27. Cluster basal area per acre (BA)
28. Point crown competition factor (CCF)
29. Point trees per acre (TPA)
30. Point basal area per acre (BA)

In addition to those observed in the field, the following data were derived for each point, cluster, and stand: trees per acre (TPA), basal area per acre (BA), and crown competition factor (CCF) (Krajicek and others 1961). The basal area percentile (BAP) for each tree was computed: the position of the tree in the basal area distribution of the stand. Also for each tree in a stand, the basal area of trees larger than the subject tree (BAL) was computed.

The growth-sample trees also provided growth information and age for any period during the life of the tree. The width of each annual ring in the increment cores was measured with the aid of an electronic measuring device (Graham 1980a). Diameter inside bark (d.i.b.) was computed for 5 years before a release treatment and for 5, 10, and 15 years after treatment, and for the years 1975 and 1979.

Table 1.—Characteristics of released western redcedar stands

		Total stand characteristics								
Stand No.	Trees tallied	Mean d.b.h.		Mean height		Trees/per		Basal area		Stand CCF
		In	*cm*	*Ft*	*m*	*Acre*	*ha*	*Ft²/acre*	*m²/ha*	
1	851	0.8	2.03	3.6	1.10	49,289	121,793	187	17.37	222
2	253	1.0	2.54	12.0	3.66	7,060	17,445	40	3.72	55
3	148	1.6	4.06	11.1	3.38	3,763	9,298	55	5.11	63
4	442	1.4	3.56	9.6	2.93	12,448	30,759	118	10.96	169
5	314	1.1	2.79	10.1	3.08	8,238	20,356	90	8.36	100
6	128	1.7	4.32	8.1	2.47	3,320	8,204	51	4.74	59
7	352	1.9	4.83	21.0	6.40	8,890	21,967	177	16.44	164
8	770	1.5	3.81	7.2	2.19	20,742	51,253	246	22.85	230
9	473	1.7	4.32	8.3	2.53	13,100	32,370	217	20.16	232
10	699	1.2	3.05	6.2	1.89	20,178	49,860	153	14.21	148
11	322	2.0	5.08	21.4	6.52	8,635	21,337	189	17.56	181
12	213	2.3	5.84	22.6	6.89	5,563	13,746	153	14.21	164
13	348	2.5	6.35	24.1	7.35	8,408	20,776	291	27.03	267
14	52	2.0	5.08	16.2	4.94	1,296	3,202	27	2.51	30
15	163	3.0	7.62	27.4	8.35	3,649	9,017	180	16.72	147

Table 2.—Characteristics of growth-sample trees in released western redcedar stands

		Growth sample trees 5-in d.b.h. and larger					
Stand No.	Number sampled	Mean d.b.h.		Mean height		Mean b.h. age	Mean b.h. age at release
		In	*cm*	*Ft*	*m*	*Yr*	*Yr*
1	35	9.1	23.11	46.9	14.30	69	24
2	22	9.7	24.64	44.0	13.41	64	53
3	25	14.6	37.08	65.9	20.09	65	43
4	33	9.4	23.88	47.6	14.51	78	60
5	28	13.4	24.04	72.7	22.16	77	28
6	22	8.9	22.61	35.1	10.70	36	17
7	59	23.4	59.44	90.4	27.55	94	74
8	81	21.1	53.59	89.8	27.37	94	74
9	54	11.7	29.72	66.6	20.30	57	33
10	39	11.0	27.94	69.9	21.31	89	69
11	46	12.1	30.73	68.3	20.82	147	125
12	36	13.6	34.54	64.8	19.75	71	56
13	69	31.8	80.77	111.0	33.83	84	60
14	14	6.5	16.51	34.3	10.45	72	54
15	38	24.6	62.48	120.2	36.41	169	159

PREDICTION OF NONRELEASED DIAMETER GROWTH

Nonreleased trees were not sampled in this study. Therefore, diameter growth prior to the release treatments was measured from the growth-sample trees and used to construct a regression model to predict nonreleased tree diameter growth. The independent variables that existed at the time of release were evaluated as potential predictors of diameter growth (table 3). To determine the optimum slope and aspect for tree diameter growth without repeated calculations, the sine of the aspect azimuth times the percent slope [Sine (Asp)*Slope] and the cosine of the aspect azimuth times the percent slope [Cos (Asp)*Slope] were used as independent variables (Stage 1976). If either the sine transformation term or the cosine transformation term was significant as an independent variable in predicting diameter growth, they both remained in the regression model.

Table 3.—The prediction model for diameter growth of nonreleased western redcedar

Nonreleased diameter growth prediction model

PGRTH = B(0) + B(1) DIA + B(2) ELEV + B(3) COSINE + B(4) SINE + B(5) SLOPE + B(6) THATFI + B(7) THPAMY + B(8) TSPAMY

where:

PGRTH	= predicted nonreleased diameter growth,
DIA	= natural log d.i.b. at beginning of growth period in mm
ELEV	= stand elevation above sea level in feet divided by 100
COSINE	= cosine of aspect azimuth in degrees times the slope in percent
SINE	= sine of aspect azimuth in degrees times the slope in percent
SLOPE	= slope in percent
THATFI	= 1 if THPL/ATFI habitat type, 0 otherwise
THPAMY	= 1 if THPL/PAMY habitat type, 0 otherwise
TSPAMY	= 1 if TSHE/PAMY habitat type, 0 otherwise

B(0) =	3.496337	B(3) =	0.007143	B(6) =	0.596686
B(1) =	1.120681	B(4) =	−0.000368 NS	B(7) =	0.538276
B(2) =	−0.018654	B(5) =	−0.022533	B(8) =	0.251484 NS[1]

$R^2 = 0.69$

Independent variables tested:

1. Stand location — geographic
2. Habitat type — TSHE/PAMY, THPL/PAMY, ABLA/PAMY, THPL/ATFI
3. Stand elevation above sea level — ft
4. Slope configuration
5. Cosine of the aspect azimuth in degrees times percent slope
6. Sine of the aspect azimuth in degrees times percent slope
7. Natural log diameter inside bark (d.i.b.) at beginning of growth period in mm
8. Breast high tree age at release in years
9. Slope in percent

Dependent variable: DDS

[1]NS = nonsignificant at $P \leq 0.05$, the variable was included because other variables of the same type were significant.

A natural log transformation of the difference between the squared diameters (DDS) was used to linearize the diameter-growth measurements as follows: $[\ln (D_1^2 - D_2^2)]$ where: D_1 equals the d.i.b. at the beginning of a growth period and D_2 equals the d.i.b. at the end of a growth period. Examinations of plots of the data and other diameter-growth models indicated a log-normal distribution for the squared differences (Wykoff[1]). Using the transformed diameter growth for a 5-year period before treatment as the dependent variable, a nonreleased diameter-growth model was fitted, using all possible regressions for the largest R^2, which in turn was evaluated stepwise for the significant ($P \leq 0.05$) independent variables. The nonreleased model is a reliable predictor of diameter growth, explaining 69 percent of the variation (table 3).

[1]Wykoff, W. R. Personal communication. Intermountain Forest and Range Experiment Station, Moscow, Idaho.

IDENTIFYING SIGNIFICANT ASSOCIATIONS

Regression analysis was used to identify the site, stand, and tree characteristics that were associated with the diameter-growth response of western redcedar. The dependent variable was the difference between observed diameter growth and the predicted nonreleased diameter growth for a tree through the same time period. Using the observed d.i.b.'s at time of release, 5, 10, and 15 years after release and for the years 1975 and 1979, four transformed 5-year diameter-growth measurements (DDS), were calculated. Using the observed growth measurements and the predicted growth measurements, the dependent variable [DDS "released"] − [DDS "predicted"] was computed. The predicted diameter growth (pred. growth) of each tree was included in each regression model to eliminate variation not related to the release response of the sampled trees. Also, if either the sine-aspect term or cosine-aspect term was significant, both terms remained in the model. The regression models could then be formulated to identify the site, stand, and tree characteristics that were associated ($P \leq 0.05$) with the difference between observed diameter growth and predicted nonreleased diameter growth of western redcedar.

Results

The diameter-growth response of western redcedar to release from overstory and surrounding competition was related to site, stand, and tree characteristics. Because tree and stand characteristics such as number of trees per acre, tree heights, and stand basal area per acre could not be estimated for past growth periods, these characteristics were used only in the regression models for the 1975-1979 growth period (table 4). Other variables such as stand elevation, slope percent, and slope configuration, were used in the regression models for all periods. The dependent variable in the models was the difference between the observed 5-year diameter growth and the predicted nonreleased 5-year diameter growth.

ZERO TO FIVE YEARS AFTER RELEASE

Five years after release, cosine of the aspect times the slope, natural log d.i.b., b.h. tree age, and the predicted nonreleased diameter growth had significant ($P \leq 0.05$) relationships with the difference between observed diameter growth and predicted nonreleased diameter growth of western redcedar. The best response of western redcedar occurred on the steep north-facing slopes and the poorest response occurred on steep south-facing slopes (fig. 2). Tree d.i.b. had a significant positive relationship with the diameter growth response

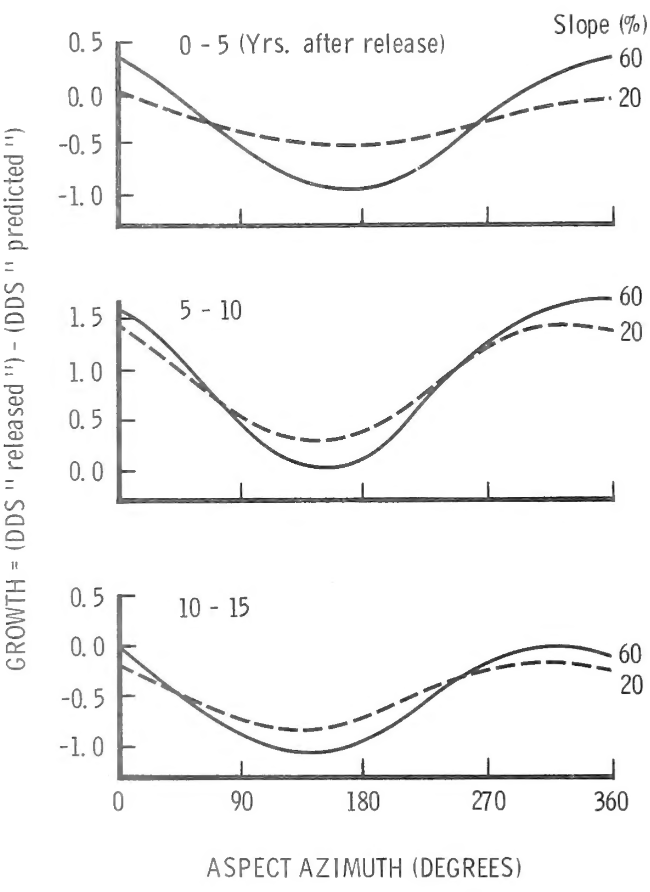

Figure 2.—The 5-year growth response of western redcedar on two slopes for three periods after stand treatment.

of western redcedar as indicated by the positive sign of the regression coefficient for the natural log d.i.b. term in the 0- to 5-year regression model (table 4). The positive sign of the natural log d.i.b. term indicated that the larger diameter western redcedar had the better response to release from competition, as compared to the smaller diameter trees. In contrast, the regression coefficient for b.h. tree age in the 0- to 5-year regression model was negative, denoting that as b.h. tree age increased, the diameter growth response of western redcedar to release decreased (table 4). Likewise, the negative coefficient for the predicted diameter growth variable provided evidence that the predicted slower growing trees had better diameter growth response to release than those with the predicted faster growth rates.

FIVE TO TEN YEARS AFTER RELEASE

Slope and aspect, along with b.h. age, had significant relationships with the difference between observed diameter growth and predicted nonreleased diameter growth of western redcedar 5 to 10 years after stand treatment. The diameter growth release response for the 5- to 10-year growth period was better on the steep north-facing slopes than on steep south-facing slopes (fig. 2) and is similar to the results for the 0- to 5-year growth period. In the 5 to 10 years after release, tree age continued to have an inverse relationship with tree response as indicated by the negative regression coefficient in the model for the 5- to 10-year period (table 4).

TEN TO FIFTEEN YEARS AFTER RELEASE

Predicted nonreleased diameter growth, sine-aspect transformation, cosine-aspect transformation, natural log d.i.b., and b.h. age were all significant ($P \leq 0.05$) variables in the observed minus predicted diameter growth model for the 10- to 15-year period (table 4). Predicted nonreleased diameter growth and tree age with negative regression coefficients remained inversely related to diameter growth release response, while natural log d.i.b. continued to have a positive relationship with the release response of western redcedar. The response to release 10 to 15 years after treatment continued to be the best on north-facing slopes and the poorest on south-facing slopes (fig. 2).

1975-79 PERIOD OF GROWTH

All of the site, stand, and tree variables were used in the regression models for the 1975-79 growth period. The number of years between the time each stand was treated and the 1975-79 growth period ranged from 10 to 45 years, with a mean time of 21 years. Stand crown competition factor, CCF, predicted nonreleased diameter growth, natural log d.i.b., b.h. age, and habitat type were variables significant in the regression model (table 4). The results for this period were similar to the results of the other growth periods, with both b.h. age and predicted diameter growth having an inverse relationship with the difference between actual tree diameter growth and predicted nonreleased tree diameter growth (table 4). Total stand CCF was significant ($P \leq 0.05$) and also had a negative regression coefficient

Table 4.—The variables associated with the difference between released and predicted nonreleased d.b.h. growth

	Significance Time period since release (years)				Regression coefficients Time period since release (years)			
Variable	0-5	5-10	10-15	1975-79	0-5	5-10	10-15	1975-79
Location	NS	NS	NS	NS[1]				
Elevation/100	NS	NS	NS	NS				
Slope angle	NS	NS	NS	NS				
Slope config.	NS	NS	NS	NS				
Time since release	NS	NS	NS	NS				
d.i.b.	NS	NS	NS	NS				
$(d.i.b.)^2$	NS	NS	NS	NS				
% sunlight	NT	NT	NT	NS				
Tree height	NT	NT	NT	NS				
Tree crown ratio	NT	NT	NT	NS				
Tree crown class	NT	NT	NT	NS				
Tree damage	NT	NT	NT	NS				
Shrub height	NT	NT	NT	NS				
% shrub cover	NT	NT	NT	NS				
BAP	NT	NT	NT	NS				
BAL	NT	NT	NT	NS				
Point BA	NT	NT	NT	NS				
Point TPA	NT	NT	NT	NS				
Point CCF	NT	NT	NT	NS				
Cluster BA	NT	NT	NT	NS				
Cluster TPA	NT	NT	NT	NS				
Cluster CCF	NT	NT	NT	NS				
Stand BA	NT	NT	NT	NS				
Stand TPA	NT	NT	NT	NS				
Stand CCF	NT	NT	NT	0.0001				– 0.008
Pred. growth	0.0001	NS	0.0046	.0001	– 1.087		– 1.489	– 1.236
Cos (Asp)*Slope	.0007	0.0038	.0012	NS	.012	0.013	.013	
Sin (Asp)*Slope	NS	.0112	.0453	NS		– .010	– .009	
ln d.i.b.	.0001	NS	.0008	.0001	1.538	2.189	1.951	
b.h. age	.0001	.0001	.0001	.0005	– .014	– .010	– .010	– .007
Habitat type	NS	NS	NS	.0108				
THPL/PAMY								.264a[2]
ABLA/PAMY								.000b
TSHE/PAMY								– 1.401b
THPL/ATFI								– .568b
Intercept					2.621	1.091	1.952	1.755
R^2					.330	.220	.310	.590

[1]NS = nonsignificant ($P \leq 0.05$)
NT = not tested
[2]Different letters indicate significant differences ($P \leq 0.05$)

indicating that stands with high CCF's had poor diameter growth response. Habitat type was also associated with the response of western redcedar to release. Trees growing on the THPL/PAMY habitat type had the best response, which was significantly different from that on the other three habitat types. There were no significant differences among the diameter growth responses of trees on the other three habitat types (table 4).

ALL GROWTH PERIODS

The magnitude of the growth response to release differed among the four growth periods. The best diameter growth occurred 5 to 10 years after a release treatment and the poorest growth for the same trees occurred between 1975 and 1979, 21 years after release (fig. 3). Likewise the proportions of trees growing faster than a predicted nonreleased tree differed among the four growth periods. The proportions for the 0-5, 5-10, 10-15, and 1975-79 periods were 51, 52, 39, and 26 percent, respectively (fig. 3).

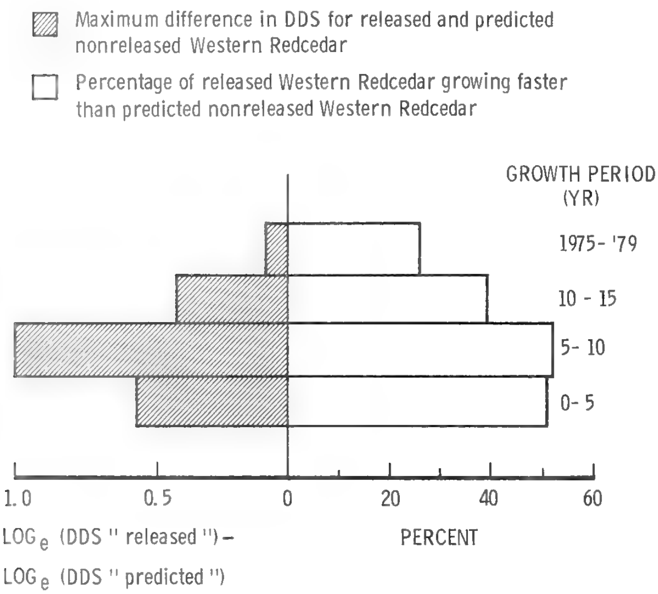

Figure 3.—Maximum difference in DDS and percentage of released western redcedar trees having a positive response.

Discussion

Diameter-growth response to release appeared to be best on north-facing slopes. Certain characteristics of growing sites on northerly exposures perhaps ameliorate changes in microclimate caused by a release cutting, thus shade-adapted leaves respond favorably to release as shown by increasing tree diameter growth. On north-facing slopes the light sensitive stomata of shade-grown leaves after a release cutting would be open less than the stomata of shade-grown leaves after a release cutting on other exposures. In addition, better leaf turgidity could be maintained, thus reducing the amount of photochemical damage to the shade leaves while new sun-adapted leaves could form. If not damaged excessively when exposed to the sun, shade leaves are capable of increasing in thickness and in weight-to-length ratios. This makes them more sun tolerant (Tucker and Emmingham 1977) and enables the tree to survive changes in microclimate. Other shade-tolerant species also respond to release best on cool, moist sites. These include grand fir (*Abies grandis* [Dougl.] Lindl.) (Ferguson and Adams 1979), amabalis fir (*Abies amabilis* [Dougl.] Forbes) (Herring and Etheridge 1976), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) (Herring 1977), and nutall oak (*Quercus nuttallii* Palmer) Johnson 1975).

Young western redcedar trees appear to respond to release from surrounding and overhead competition better than older trees. Several factors could be involved in changing this relationship, including natural senescence, crown depletion resulting from suppression, and damage due to many kinds of agents. When shade-tolerant trees are grown for long periods in suppressed conditions, their crowns develop to be shorter and thinner than their open-grown counterparts. Because trees with long, dense crowns are the most vigorous they are more likely to respond to release (Graham 1980b; Seidel 1977). Understory western redcedar are often subjected to heavy snow loads that damage the crowns and boles, thus decreasing their ability to respond to release. The capacity of a tree to respond to release generally declines with age (Baker 1950; Ferguson and Adams 1979), but age does not appear to affect the release of some species such as subalpine fir and balsam fir (*Abies balsamea* [L.] Mill.) (Herring 1977).

The larger diameter western redcedar trees in a stand had the better diameter growth responses to release. The larger diameter trees in a stand are usually the taller trees with larger crowns, have more crown that is sun adapted, and have more extensive root systems. Therefore, when a release cut occurs in a stand those trees with larger diameters can respond to the more favorable growing conditions more quickly than smaller trees. The faster growing western redcedar in a stand may have adequate growing space before a release treatment, so any additional space from release cutting would not be utilized. Therefore, prereleased diameter growth rates do not always indicate, as well as d.b.h. does, the growth performance after release. This has also been demonstrated by Baker (1950), Cole and Stage (1972), and Stage (1973).

The diameter-growth response of western redcedar to release was significantly ($P \leq 0.05$) related to habitat types. Western redcedar on the THPL/PAMY habitat type had the best release response. This is the warmest and driest habitat type where western redcedar grows (Daubenmire and Daubenmire 1968). Western redcedar is the climax species on this habitat type and can dominate in eventual size and number over the other species. On the TSHE/PAMY habitat type, western redcedar cannot compete with the other species as readily when released. Any disturbance in stands growing on the TSHE/PAMY habitat type usually results in a tremendous western hemlock regeneration that can compete with the released western redcedar trees. The occurrence of western redcedar on the ABLA/PAMY habitat type is very limited, making release operations marginal. It appears that on this habitat type, western redcedar is limited by cold temperatures. Any release cutting will increase the probability of frost damage to the released trees, making the release treatments less effective. Likewise release treatments on the THPL/ATFI habitat type could be less successful because of cold temperatures and high ground-water tables. Habitat types have also been found related to

the growth of other species (Stage 1973; Stage 1976) as well as to release response of other species (Ferguson and Adams 1979).

Stand density after release was related to the amount of diameter growth western redcedar achieves. Western redcedar stands with high CCF's after release had growth rates less than western redcedar stands with low CCF's. Increases in stand density after release can be partially attributed to additional tree growth in response to the treatment and to new regeneration.

The stresses in western redcedar as it adjusts to a new microclimate after a release cutting could make it more susceptible to attack by *Armillaria mellea* (Vahl. ex Fr.). *Armillaria mellea* is capable of spreading by both root-to-root contact and by rhizomorphs infecting other stump and tree root systems (Boyce 1961; Morrison and Johnson 1978). Frequency of such contact is increased in response to release; i.e., western redcedar's extensive grafted root system expands along with the expansion of ingrowth root systems. This helps facilitate the spread of *A. mellea* throughout the released stand. The mechanical operations of a release treatment can increase the infection rate of *Fomes annosus* (Fr.) Karst. and *Heterobasidion annosum* (Fr.) Bref. in stands of western hemlock (Wallis and Morrison 1975; Chavez and others 1980), but there is no evidence that mechanical damage increases the infection rate of *A. mellea* in released stands. Increasing tree spacing by release cuttings does not prevent the attack of western recedar by *A. mellea*, but it can actually increase disease infection rates.

SOIL CHARACTERISTICS ASSOCIATED WITH THE RELEASE RESPONSE OF WESTERN REDCEDAR

Literature Review

Few significant associations between individual tree growth and soil characteristics have been reported. White and Leaf (1964, 1965) could not relate height growth to amounts of total soil potassium but could relate height growth to potassium levels near the solum bottom. Amounts of soil phosphorus have been found related (Hopmans and others 1978) and unrelated (Pritchett and Llewellyn 1966) to tree growth. In contrast, relating soil characteristics to site index has been successful, resulting in several soil-site systems available for evaluating site productivity (Gessel and Lloyd 1950; Alban 1974). Often these soil-site evaluation systems include other nonsoil variables such as elevation and aspect that make their productivity predictions more reliable (Steinbrenner 1979). Depending upon location and species, tree growth has been found related to the amount of nutrients added to soil through fertilization (Mayer-Krapoll 1956; USDA 1973).

Methods

DATA COLLECTION

An integrated soil sample of the top 12 inches (30.5 cm) of mineral soil was collected from each of the 5 points within a cluster. The upper 12 inches (30.5 cm) of soil has been shown to include the largest proportion of conifer roots (Powers 1976; Eis 1974). The samples were then combined in a shaker to form one soil sample for each stand. The composite samples for each stand were then chemically analyzed by the University of Idaho College of Agriculture Plant and Soil Analytical Laboratory. These chemical analyses quantified 14 characteristics of the soils from the 15 released stands of western redcedar (table 5).

Table 5.—Chemical characteristics of the soil from 15 stands of released western redcedar

Characteristic	Mean	Standard deviation	Maximum	Minimum
pH	5.70	0.37	6.15	5.05
Phosphorus (ppm)	3.00	1.90	6.80	1.00
Potassium (ppm)	2448.00	788.50	3800.00	1190.00
Organic matter (%)	9.13	2.99	14.60	4.60
Nitrate (ppm)	1.20	1.48	5.20	.10
Ammonium (ppm)	4.61	2.12	9.40	2.00
Electrical cond. (μ mhos)	.15	.06	.34	.09
Boron (ppm)	.09	.06	.19	.00
Sulfate (ppm)	8.50	5.00	31.00	4.00
Zinc (ppm)	2.86	1.09	5.88	1.68
Manganese (ppm)	134.30	48.20	198.00	39.00
Copper (ppm)	1.06	.38	1.80	.60
Iron (ppm)	367.60	113.00	600.00	246.00
Total nitrogen (%)	.25	.09	.48	.13

IDENTIFYING SIGNIFICANT ASSOCIATIONS

Regression analysis was used to identify the soil variables significantly associated with the release of western redcedar. The dependent variable in the regression models was the difference between the DDS for released trees and the predicted nonreleased DDS for the same tree (DDS "released" – DDS "nonreleased"). Fourteen soil variables were tested for association with the dependent variable. The predicted diameter growth of each tree was included in each regression model to eliminate variation not related to the release response of the sample trees. Transformed diameter increments for the periods 0-5, 5-10, and 10-15 years after treatment were used as dependent variables in the regression models.

Results

Amounts of several soil nutrients and soil pH were associated ($P \leq 0.05$) with the growth difference between released diameter growth and predicted nonreleased diameter growth of western redcedar. Amounts of soil nitrogen were significantly related to the difference between released diameter growth and the predicted nonreleased diameter growth of western redcedar as denoted by the significant coefficients for the nitrogen variables (table 6). The positive regression coefficients for the nitrate and ammonium variables in the regression models indicated that trees growing on soils with larger amounts of these forms of soil nitrogens had greater release response than trees growing on soils with lesser amounts of ammonium and nitrate. In contrast, amounts of total soil nitrogen were negatively associated with western redcedar diameter-growth response to release. In other words, trees growing on soils with the larger amounts of total nitrogen had poorer diameter growth release response when compared to trees growing on soils with lesser amounts of total nitrogen.

Amounts of soil sulfate and potassium showed positive relationships with the release of western redcedar from overhead and surrounding competition. Both sulfate and potassium had positive regression coefficients in the 0-5- and 10-15-year models (table 6). The regression coefficients indicated that western redcedar growing on soils with the larger amounts of sulfate and potassium had greater diameter growth response to release than western redcedar growing on soils having lesser amounts of sulfate and potassium.

Amounts of soil iron and copper, along with soil pH, had negative relationships with the diameter increment of released western redcedar. The regression coefficients for soil iron, and copper were significant only for 0-5- and 5-10-year periods, with the regression coefficient for soil pH being significant for all growth periods (table 6). These regression coefficients were evidence that the response of western redcedar to release was greater on soils with the lesser amounts of copper, iron, and lower pH values, compared to tree diameter growth on soils with the larger amounts of copper, iron, and higher pH values.

Significant interactions between soil characteristics were detected using two variable regression models. For the 0-5-year time period since release the significant interactions identified were total nitrogen-iron and pH-potassium (table 7). During the 5-10-year time period, the significant interactions detected were total nitrogen-copper, total nitrogen-iron, pH-iron, total nitrogen-potassium, pH-sulfate, and total nitrogen-nitrate. Only two significant interactions, total nitrogen-potassium and pH-ammonium, were detected for the 10-15-year period. The significant interactions were evidence that for a given amount of soil constituent the response of western redcedar to release was not proportional to changes of the other constituent in the interaction.

Discussion

Several soil characteristics were significantly ($P \leq 0.05$) associated with the growth difference between the diameter of released western redcedar and the predicted diameter growth of nonreleased western redcedar. Soil variables, including total nitrogen, ammonium, nitrate, sulfate, copper, potassium, iron, and pH had significant regression coefficients in the release response models.

Soil pH directly influences the uptake of soil nutrients by plants. Soil copper, boron, zinc, manganese, potassium, and iron are not readily absorbed by plants at higher soil pH's (Alban 1958). The influence that soil pH has on the availability of soil nutrients for plant growth could explain why western redcedar growing on high pH soils had the poorer response to release. Soil pH could be limiting the uptake of soil nutrients, thereby influencing the diameter increment of released trees. Data for this study did show interactions of pH and potassium having negative relationships with the response of western redcedar to release.

Nitrogen nutrition of forest trees is usually more complex than is the nutrition of other major elements. Nitrogen is most readily available for tree growth in the nitrate and ammonium forms that often can be less than 10 percent of the total nitrogen in a forest soil (Jorgensen 1967). Much of the total nitrogen is immobile or nearly so in organic matter and long periods of time are involved in its breakdown (Shoulders and McKee 1973). Switzer and others (1968) showed that soils of a southern pine ecosystem contained 1,700 lb (1 905 kg/ha) of total nitrogen per acre but only 34 lb (38 kg/ha) per acre were available for tree growth. Therefore it would be possible for western redcedar to have a greater response to release on soils with the greater amounts of available nitrogen, but also a poor response to release on soils with the large amounts of total nitrogen because it is possible that only a small amount of the total soil nitrogen was available for tree growth.

Relationships of tree growth to soil nutrients can easily be confounded by other tree and site variables. Elevation and aspect can influence the availability of soil nutrients (Leaf 1956), as can the tree genotype (Steinback 1971). Likewise, tree rooting habit and the ability of tree roots to penetrate forest soils can affect

Table 6.—Soil characteristics associated with the difference between released and predicted nonreleased growth

Variables	Significance Time period since release (years)			Regression coefficients Time period since release (years)		
	0-5	5-10	10-15	0-5	5-10	10-15
Organic matter (%)	NS	NS	NS[1]			
Phosphorus (ppm)	NS	NS	NS			
Electrical cond. (μmhos)	NS	NS	NS			
Boron (ppm)	NS	NS	NS			
Zinc (ppm)	NS	NS	NS			
Manganese (ppm)	NS	NS	NS			
Nitrogen (%)	0.0031	0.0001	0.0001	−2.1187	−4.5781	−6.5043
Ammonium (ppm)	NS	NS	.0373			.0650
Nitrate (ppm)	NS	.0001	NS		.2877	
Sulfate (ppm)	.0001	.0001	NS	.0989	.2303	
Copper (ppm)	.0001	.0001	NS	− .8020	− .9213	
Potassium/100 (ppm)	.0001	.0001	.0001	.0599	.1256	.0471
Iron (ppm)	.0263	.0001	NS	− .0010	− .0045	
pH	.0001	.0001	.0001	−1.4210	−3.1132	−1.0853
Predicted growth	.0004	.0001	.0001	.1792	.2742	.3295
Intercept				7.1217	16.1760	− .3380
R^2				.34	.49	.31

[1]NS = nonsignificant ($P \leq 0.05$)
Coefficients not estimated for nonsignificant variables.

Table 7.—Selected models to test interactions between soil nutrients

Model Form: ln (DDS "released") − ln (DDS "nonreleased") = Predicted growth + variable (1) + variable (2) + variable (1)*variable (2)

Variable interaction	Significant regression coefficients Time period since release (years)		
	0-5	5-10	10-15
Total N*K	NS[1]	−0.2780	−0.2857
Total N*Sulfate	NS	NS	NS
Total N*Cu	NS	2.4658	NS
Total N*Fe	0.0220	.0317	NS
Total N*pH	NS	NS	NS
Total N*Ammonium	NS	NS	NS
Total N*Nitrate	NS	−1.9135	NS
pH*Sulfate	NS	− .1911	NS
pH*Cu	NS	NS	NS
pH*Fe	NS	.0065	NS
pH*K	.3591	NS	NS
pH*Nitrate	NS	NS	NS
pH*Ammonium	NS	NS	− .1327

[1]NS = nonsignificant ($P \leq 0.05$)
Coefficients not estimated for nonsignificant variables.

nutrient uptake (Armson 1965). Stand treatments, such as cleaning, weeding, and thinning, can alter tree-growth nutrient relationships (Zinke 1962; Gagnon 1964). Also, methods used to assess fertility of agricultural soils when used for forest soils may result in erroneous data (Waring and Youngberg 1972). To better assess soil fertility of forest soils, Leaf and Madgwick (1960) suggested modifying agricultural soil tests by including soil volume to better express soil fertility.

Because of these problems, total quantities of soil nutrients in forest soils can seldom be related easily to tree growth (Ralston 1964) as shown by Ballard and Pritchett (1975) and Pritchett and Llewellyn (1966). For these reasons it is important to evaluate carefully the diameter growth response of western redcedar in relation to soil nutrient quantities. The regression models provided evidence that certain soil nutrients were related to the release response of western redcedar.

TREE FOLIAGE CHARACTERISTICS ASSOCIATED WITH THE RELEASE OF WESTERN REDCEDAR

Literature Review

Foliar nutrient concentrations can be mathematically related to various forms of tree growth. Using multiple regression techniques, Leyton and Armson (1955) determined the critical threshold amounts of foliar nitrogen and potassium for height growth of Scots pine (*Pinus sylvestris* L.). The same methods were used to estimate Japanese larch (*Larix leptolepsis* Murr.) height growth as a function of foliar nutrient concentrations (Leyton 1956). Foliar nutrient quantities can be used to predict basal area, height, and volume growth of red pine (*Pinus resinosa* Ait.) (Hoyle and Mader 1964). Likewise, amounts of nutrients in leaf parts are related to the height and volume growth of sycamore (*Platanus occidentalis* L.) (Haines and others 1979). Using entire tree populations, Stone and others (1958) used foliar nutrient concentrations to predict stand volume. Foliar concentrations of different nutrients can be used to predict site index as demonstrated by Gagnon (1964) and Radwan and DeBell (1980).

Mathematical models predicting tree growth using foliar nutrients can help identify amounts of foliar nutrients that limit tree growth. The relationships of tree growth to foliar nutrient concentrations have been divided into a region of deficiency, a region of critical amounts, and a region of luxury consumption (Barrows 1959; Richards and Bavege 1972; Everard 1973). Leyton (1958), when investigating critical and nutrient requirements for tree growth, found it easier to detect critical nutrient amounts than to find optimum amounts or to predict fertilizer response.

Critical and deficient amounts of foliar nutrients for fruit production have been thoroughly investigated (Sprague 1964) and are continually being refined for different crops and soils (Jones and others 1968; Embleton and Jones 1966; Embleton and others 1971).

Foliage nutrient concentrations for many eastern conifer (Lowry and Avard 1968, 1969; White 1954), and southern conifer (Wells and Metz 1963) populations have been reported. Foliar nutrient concentrations for northwest conifers have been reported by Tarrant and others (1951), Daubenmire (1953), and Beaton and others (1965).

In addition to sampling the natural variation of foliar nutrients of different species, more specific studies were conducted on foliar nutrient deficiencies in conifers. Van den Burg (1979) reported foliar deficiency levels for nitrogen, phosphorus, potassium, magnesium, and manganese in three spruce species. Likewise, Gessel and others (1951) reported preliminary results that identified foliar nutrient deficiencies for western redcedar, and later Walker and others (1955) finalized the mineral requirements for western redcedar. Powers (1976) summarized the deficient and critical foliar nutrient concentrations for conifers, hardwoods, and field crops.

Besides establishing deficiency levels of nutrients for tree growth, many studies have also reported the foliar symptoms of nutrient deficiencies. Foliar nutrient deficiencies of hardwoods have been described by Ashby (1959), Ashby and Mika (1959), Hacskaylo and Struthers (1959), Ike (1968), Phares and Finn (1972), Smith (1976), Perala and Sucoff (1965), and Mader and others (1969). Foliar symptoms of mineral deficiencies of conifers have been described by Walker and others (1955), White and Wright (1966), and Behan (1968).

Methods

DATA COLLECTION

A sample of the most recent foliage was collected at a height of 12 feet (3.7 m) and from the north side of each western redcedar tree on the variable radius plots. As the foliage was collected, its color was identified using the Munsell color notation system (Munsell Color Company 1952; Hamilton 1960). The foliage was kept cold until it was chemically analyzed by the University of Idaho College of Agriculture Plant and Soil Analytical Laboratory. These chemical tests resulted in amounts of 12 foliar nutrients for 601 western redcedar trees in this study (table 8).

IDENTIFYING SIGNIFICANT ASSOCIATIONS

Regression analysis was used to identify the foliar variables significantly associated with the release of western redcedar. The dependent variable in the regression models was the difference between the DDS for released trees and the predicted nonreleased DDS for the same tree (DDS "released" − DDS "nonreleased"). Twelve foliar variables were tested for association with the dependent variable. The predicted diameter growth of each tree was included in each regression model to eliminate variation not related to the release response of the sampled trees. The transformed diameter increment for the 10 years after treatment was used as the dependent variable in the regression models.

Foliar nutrient content was separated by foliar color using discriminant analysis in which 11 Munsell foliar colors and 12 foliar nutrients were used.

Results

The diameter-growth responses of 601 western redcedars to release from overstory and surrounding competition were related to foliar characteristics. Amounts of phosphorous and manganese in foliage of western redcedar had positive, significant relationships with the differences between released diameter growths and predicted nonreleased diameter growths. These relationships were indicated by the positive significant coefficients in the regression models for the phosphorus and manganese variables (table 9). These coefficients were evidence that western redcedar having foliage with the greater amounts of manganese and phosphorus had greater diameter growth response to release than western redcedar having foliage with smaller amounts of manganese and phosphorus.

Foliage concentrations of iron, sodium, potassium, and sulfur had negative significant relationships with the differences in diameter growths of released and predicted nonreleased western redcedars. The negative regression coefficients for foliar iron, sodium, potassium, and sulfur indicated that the diameter increment of released trees with the higher concentrations of

Table 8.—Amounts of foliar nutrients for 601 released western redcedar trees

Nutrient	Mean	Standard deviation	Maximum	Minimum
Zinc (ppm)	16.02	3.01	23.80	11.00
Manganese (ppm)	130.54	34.90	225.00	75.00
Copper (ppm)	5.04	1.16	7.50	2.50
Iron (ppm)	159.14	75.75	488.00	88.00
Sodium (ppm)	234.36	89.79	403.00	115.00
Potassium (ppm)	5,938.25	1,210.12	8,800.00	4,100.00
Calcium (ppm)	12,678.57	3,441.61	23,000.00	8,500.00
Magnesium (ppm)	1,003.57	173.83	1,225.00	600.00
Sulfur (ppm)	380.68	41.77	468.00	309.00
Boron (ppm)	13.97	3.54	22.65	9.15
Nitrogen (%)	.90	.12	1.15	.63
Phosphorus (%)	.13	.01	.15	.09

Table 9.—Foliar nutrients associated with the difference between released and predicted nonreleased d.b.h. growth

Nutrient	Coefficient	Significance
Zinc (ppm)		NS[1]
Manganese (ppm)	0.0034	0.0008
Copper (ppm)		NS
Iron (ppm)	− .0033	.0001
Sodium (ppm)	− .0042	.0001
Potassium (ppm)/100	− .0240	.0001
Calcium (ppm)		NS
Magnesium (ppm)		NS
Sulfur (ppm)	− .0121	.0001
Boron (ppm)		NS
Nitrogen (%)		NS
Phosphorus (%)	55.9794	.0001
Predicted growth	.1999	.0001
Intercept	−2.0210	.0001
R^2	.371	

[1]NS = nonsignificant ($P \leq 0.05$)
No coefficients given for nonsignificant variables.

these foliar nutrients was less than the diameter increment of released trees with the lower concentrations.

Using two variable regression models, selected interactions between foliar nutrients were tested. Total nitrogen and phosphorus appeared to have no significant interactions with other foliar nutrients when their association with the release response of western redcedar was tested, as shown in the following tabulation:

Variable interaction	Significant coefficient
Mg* P	NS
Mn* P	NS
N* P	NS
N* Fe	NS
N* Na	NS
N* S	NS
N* Mg	NS
N* Mn	NS
N* K	NS

NS = non-significant ($P \leq 0.05$)
Model Form: ln (DDS "released") − ln (DDS "nonreleased") = Predicted growth + variable (1) + variable (2) + variable (1)*variable (2)

The colors of western redcedar foliage were associated with the growth difference between released and predicted nonreleased tree diameter growths. Six percent of the variation in the difference between released and predicted nonreleased diameter growth of western redcedar was accounted for in the analysis by foliar color. Western redcedar trees with green-yellow foliage had a diameter growth-response-mean of −0.156, whereas trees with greenish green-yellow foliage had the response mean of −0.874 (table 10). Significant differences were detected in the time-adjusted growth response means for the different foliar colors. Three groups of foliar-color-classified growth response means were separated. Trees having green-yellow foliage dominated the group with the larger growth response means (a); trees with green-yellow foliage and yellowish-green foliage dominated the middle group of growth response means (b); and trees with green-yellow, greenish green-yellow and yellowish-green-yellow foliage occupied the group with the smaller growth response means (c) (table 10).

Western redcedar foliage classified by color had different mean concentrations of foliar nutrients. Deficient concentrations of foliar nutrients are as

Table 10.—Least squares diameter growth response means for different foliar colors

Color[1]			Color description	Growth response[2] Least squares mean
Hue	Value	Chroma		
5.0 GY	7	8	Green-yellow	−0.156 a [3]
2.5 GY	5	6	Yellowish green-yellow	−.284 a b
5.0 GY	7	10	Green-yellow	−.354 a b
5.0 GY	6	8	Green-yellow	−.362 a b
5.0 GY	6	6	Green-yellow	−.419 a b c
5.0 GY	4	6	Green-yellow	−.497 a b c
2.5 GY	6	8	Yellowish green-yellow	−.566 b c
5.0 GY	5	8	Green-yellow	−.623 b c
7.5 GY	6	10	Greenish green-yellow	−.649 b c
2.5 GY	7	8	Yellowish green-yellow	−.660 b c
7.5 GY	5	6	Greenish green-yellow	−.874 c

[1]Munsell color notation (Munsell Color Company 1952).
[2]Adjusted for time since treatment.
[3]Different letters indicate significant differences ($P \leq 0.05$).

Table 11.—Mean foliar nutrient content associated with foliar colors of western redcedar

Color[1]			Element											
H	V	C	N	P	B	Fe	K	Ca	Mg	S	Cu	Zn	Mn	Na
			Percent		Parts/million									
2.5GY	5	6	0.79	0.11	11.8	170.0	5,033	17,077	922	362	14.9	20.2	146	195
2.5GY	7	8	.91	.12	14.1	147.9	5,979	14,375	1,055	386	8.9	18.3	127	202
2.5GY	6	8	.91	.12	14.1	150.3	5,642	14,210	1,055	377	8.2	17.2	119	230
5.0GY	6	6	.85	.12	13.0	151.5	5,606	14,930	1,016	371	6.9	17.1	129	228
5.0GY	4	6	.95	.13	15.0	172.4	6,446	13,405	1,037	393	5.0	18.1	131	203
5.0GY	7	8	.93	.13	13.7	129.6	6,227	13,032	999	390	4.8	16.2	127	192
5.0GY	6	8	.90	.13	14.2	159.4	6,030	13,158	1,018	376	7.1	16.5	133	238
5.0GY	5	8	.93	.13	15.1	168.0	6,096	12,170	1,006	391	8.1	16.7	134	255
5.0GY	7	10	.98	.13	16.0	138.6	7,134	11,037	1,088	410	11.2	17.6	135	227
7.5GY	5	6	.90	.12	14.8	217.7	5,227	15,427	1,043	415	5.0	15.3	139	230
7.5GY	6	10	.94	.12	16.8	154.0	5,923	13,795	1,154	387	14.9	15.2	116	324
Deficiency level			<1.50[2]	.40[2]	15.0[2]	10-80[2]	3,910 – 7,820[2]	1,000 – 2,000[2]	608 – 1,890[2]	2,402 – 4,804[2]	<3.0[3]	<5.0[3]	<16[4]	?

[1]Munsell color notation (Munsell Color Company 1952).
[2]Walker and others (1955).
[3]For conifers (Powers 1976).
[4]For citrus crops (Reiseanauer 1976).

Table 12.—Significant differences in mean nutrient content by foliar color

Color[1]														
Hue	Value	Chroma	No.	1	2	3	4	5	6	7	8	9	10	11
2.5 GY	5	6	1	• [2]										
2.5 GY	7	8	2	—	•									
2.5 GY	6	8	3	D	—	•								
5.0 GY	6	6	4	D	—	—	•							
5.0 GY	4	6	5	D	—	D	D	•						
5.0 GY	7	8	6	D	—	D	D	—	•					
5.0 GY	6	8	7	D	—	D	D	—	D	•				
5.0 GY	5	8	8	D	D	D	D	D	D	D	•			
5.0 GY	7	10	9	D	—	D	—	—	D	D	D	•		
7.5 GY	5	6	10	D	D	D	D	D	D	D	D	D	•	
7.5 GY	6	10	11	D	D	D	D	D	D	D	D	D	D	•

[1]Munsell color notation (Munsell Color Company 1952).
[2]D = significant differences at ($P \leq 0.05$) for 12 nutrients: B, Fe, N, P, K, Ca, Mg, S, Cu, Zn, Mn, Na.

follows: boron, 15 ppm; nitrogen, 1.50 percent; phosphorus, 0.40 percent; and sulfur, 2,402 ppm (Walker and others 1955) (table 11). In the foliage of released western redcedar, however, concentrations were found to be low: boron, 11.8 ppm; nitrogen, 0.79 percent; phosphorus, 0.11 percent; sulfur, 362 ppm. Also foliar amounts of potassium and magnesium approached the deficiency concentrations reported by Walker and others (1955) for western redcedar.

Discriminant analysis simultaneously detected differences in the mean nutrient contents for 12 different nutrients in the foliage of released western redcedar. Foliage with colors 5.0 GY 5/8, 7.5 GY 5/6, and 7.5 GY 6/10 were individually unique in nutrient content (table 12). Likewise, foliage with color 2.5 GY 5/6 had significantly different nutrient content than all other colored foliage except foliage with color 2.5 GY 7/8.

Discussion

Western redcedar foliar characteristics were related to the differences between released and predicted nonreleased tree diameter growths. Amounts of foliar manganese, iron, sodium, potassium, sulfur, and phosphorus were significantly ($P \leq 0.05$) related to the diameter growth response of western redcedar.

The antagonistic effect of one plant nutrient to another plant nutrient could explain some of the relationships between foliar nutrients and the response of western redcedar to release. Foliar phosphorus had a positive significant relationship with the release response of western redcedar and also appeared to be deficient when compared to the amounts reported by Walker and others (1955). Magnesium can restrict the uptake and accumulation of phosphorus by trees (Gysi and others 1975). In contrast, in the data presented here on the release of western redcedar, an interaction between magnesium and phosphorus could not be detected. Although an interaction could not be detected, larger amounts of foliar magnesium could possibly result in larger amounts of foliar phosphorus, which in turn could result in greater diameter growth response of western redcedar to release.

The negative relationship of foliar potassium to the release response of western redcedar from competition could be caused by the deficient amount of nitrogen found in the western redcedar foliage. Nitrogen is known to interfere with the uptake and accumulation of potassium in tree foliage (Brendenmuehl 1968; Benzian and Freeman 1967). Therefore, the negative relationship of potassium to release could actually be a nitrogen deficiency expressed by potassium even though an interaction between potassium and nitrogen could not be detected. Perhaps no interaction was detected because potassium is highly mobile within a tree (Bukovac and Wittwer 1957); therefore, adequate amounts for foliage metabolism can be supplied through redistribution within the tree (Switzer and Nelson 1972).

The nitrogen deficiencies that appeared in the foliage of released western redcedar could also cause the negative relationships of sodium and sulfer to the release responses of western redcedar. Concentrations of both sulfur and sodium in the tree foliage can be affected by concentrations of foliar nitrogen (Shoulders and McKee 1973). As with potassium no interaction between nitrogen and sodium or sulfur could be detected.

The color of western redcedar foliage after release also reflects the amount of nutrients accumulated in the foliage. Foliage with three different colors as distinguished by Munsell Color Company (1952) notation contained nutrient amounts which differed from each other and from the foliage with eight other colors. The relationships of foliar colors and amounts of foliar nutrients to release could easily be altered by release operations. Increased amounts of organic matter in the form of leaves, branches, and boles of trees left after a release cutting could easily change the uptake and accumulation of nutrients. Nitrogen and other nutrients can be tied up in the breakdown of organic matter, making such nutrients unavailable for tree growth. As little as 2 percent of total nitrogen can be available for tree growth, with the remainder involved in the breakdown of organic matter (Shoulders and McKee 1973). In turn, the different amounts of accumulated nutrients in the foliage of the released western redcedar could alter foliage color.

Western redcedar with the more yellow foliage showed the best response to release. Such trees were probably more open grown than others, which resulted in both the better diameter growth and the more yellow foliage. In contrast, the trees with the slower diameter growth probably grew in the more dense portions of the stands, which resulted in both the slower growth rates and greener foliage.

Foliar properties appear to be significantly related to the differences between the diameter increment of released western redcedar and the predicted diameter increment of nonreleased western redcedar. Nutrient needs and accumulation might deserve consideration when preparing cutting prescriptions for stands of western redcedar, and also when planning future research into the response of western redcedar to release.

CONCLUSIONS

The diameter increments of western redcedar increase in response to release from overhead and surrounding competition. Several site, stand, and tree characteristics were significantly ($P \leq 0.05$) associated with the differences between diameter increments of released trees and predicted diameter increments of nonreleased trees.

Several site characteristics are important considerations in developing treatment alternatives for releasing western redcedar. Stands growing on the *Thuja plicata/Pachistima mrysinites* habitat type had the best response to release compared to trees growing on other habitat types. Trees growing on steep north slopes had greater growth after release compared to trees growing on other slopes and aspects. Likewise, trees growing on soils with larger amounts of nitrate, ammonium, sulfate, and potassium had greater growth

after release when compared to trees growing on soils having smaller amounts of these nutrients.

Tree characteristics were also associated with the release response of western redcedar. The larger the tree diameter at the time of release the greater was its growth after release. Also, the younger the tree at the time of release the better its growth after release.

Foliage color was associated with tree growth and nutrient content of the foliage. Trees with green-yellow foliage had greater growth rates than trees with greenish-yellow foliage. Discriminant analysis simultaneously detected differences in mean nutrient contents for 12 different nutrients in the foliage of released western redcedar.

The results of this study emphasize the importance of site, stand, and tree characteristics in the amount of response western redcedar trees have after they are released from overhead and surrounding competition. The species will respond favorably to release, depending on tree size, tree age, habitat type, slope, aspect, and soil nutrient content.

PUBLICATIONS CITED

Alban, L. A. Interpretation of soil tests. Circ. Inf. 587. Corvallis, OR: Oregon State Univ. Agriculture Experiment Station; 1958. 11 p.

Alban, D. H. Red pine site index in Minnesota as related to soil and foliar nutrients. For. Sci. 20: 261-269; 1974.

Armson, K. A. Seasonal patterns of nutrient absorption by forest trees. *In:* Forest-soil relations in North America. Corvallis, OR: Oregon State Univ. Press; 1965: 65-76.

Ashby, William C. Limitation to growth of basswood from mineral nutrient deficiencies. Bot. Gaz. 121: 22-28; 1959.

Ashby, W. C.; Mika, E. S. Sulfur deficiency in *Tilia americana*. Bot. Gaz. 121: 28-31; 1959.

Aussenac, G. Effect of different microclimates on the morphology and structure of needles. Ann. Sci. For. 30: 375-392; 1973.

Baker, F. S. Principles of silviculture. New York: McGraw-Hill; 1950: 51-59.

Ballard, R.; Pritchett, W. L. Soil testing as a guide to phosphorus fertilization of young pine plantations in the coastal plain. Bull. 778. Gainesville, FL: University of Florida, Agriculture Experiment Station; 1975. 22 p.

Barrows, H. L. Evaluating the micronutrient requirements of trees. *In:* Mineral nutrition of trees: a symposium. Bull. 15. Durham, NC: Duke University, School of Forestry; 1959: 18-31.

Beaton, J. D.; Moss, A.; MacRae, I.; Konkin, J. W.; McGhee, W. P. T.; Kissick, R. Observations on foliage nutrient content of several coniferous tree species in British Columbia. For. Chron. 41: 223-236; 1965.

Behan, M. J. Visual diagnosis of mineral deficiency in western larch. Bull. 34. Missoula, MT: Montana State University, School of Forestry; 1978. 7 p.

Berry, A. B. How plantation white spruce responds to crown thinning. Can. For. Ind. 1968(8): 20-22; 1968.

Benzian, B.; Freeman, S. C. R. Effect of "late season" N and K top dressings applied to conifer seedlings and transplants, on nutrient concentrations in the whole plant and on growth after transplanting. *In:* Report on forest research for the year ending March 1967. London: Forestry Commission of Great Britain, H. M. Stationery Office; 1967: 135-140.

Bolsinger, C. L. Western redcedar—a forest in transition. Resour. Bull. PNW-85. Portland OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1979. 24 p.

Boyce, J. S. Forest pathology. New York: McGraw-Hill; 1961: 51.

Brendenmuehl, R. H. Research progress in the use of fertilizers to increase pine growth on the Florida sandhills. *In:* Forest fertilization-theory and practice. Muscle Shoals, AL: Tennessee Valley Authority; 1969: 191-196.

Bukovac, M. J.; Wittwer, S. H. Absorption and mobility of foliar applied nutrients. Plant Physiol. 32: 428-435; 1957.

Carvell, K. L. The response of understory oak seedlings to release after partial cutting. Bull. 553. Morgantown WV: Agriculture Experiment Station; 1967. 20 p.

Chavez, T. D., Jr.; Edmonds, R. L.; Driver, C. H. Young-growth western hemlock stand infection by *Heterobasidion annosum* 11 years after precommercial thinning. Can. J. For. Res. 10: 389-394; 1980.

Cole, D. M.; Stage, A. R. Estimating future diameters of lodgepole pine trees. Res. Pap. INT-31. Ogden, UT: U.S. Department of Agriculture Forest Service, Intermountain Forest and Range Experiment Station; 1972. 20 p.

Crossley, D. I. Growth response of spruce and fir to release from suppression. For. Chron. 52: 189-193; 1976.

Daubenmire, R. Nutrient content of leaf litter of trees in the Northern Rocky Mountains. Ecology. 34: 786-793; 1953.

Daubenmire, R.; Daubenmire, J. B. Forest vegetation of eastern Washington and northern Idaho. Tech. Bull. 60. Pullman, WA: Washington Agriculture Experiment Station; 1968. 104 p.

Deitschman, G. H.; Pfister, R. D. Growth of released and unreleased young stands in the western white pine type. Res. Pap. INT-132. Ogden UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1973. 14 p.

Eis, S. Root grafts and their silvicultural implications. Can. J. For. Res. 2: 111-120; 1972.

Eis, S. Root system morphology of western hemlock, western redcedar, and Douglas-fir. Can. J. For. Res. 4: 28-38; 1974.

Embleton, T. W.; Jones, W. W. Avacado and mango nutrition. N. F. Childers, ed. *In:* Fruit nutrition. New Brunswick, NJ: Horticultural Publications, Rutgers-The State University; 1966: 51-76.

Embleton, T. W.; Jones, W. W.; Labanauskas, C. K.; Platt, R. G. Leaf analysis and phosphorus fertilization of oranges. Citrograph 56: 101-124; 1971.

Everard, J. Foliar analysis. Sampling methods, interpretation and application of the results. Q. J. For. 67: 51-66; 1973.

Ferguson, D. E.; Adams, D. L. Guidelines for releasing advanced grand fir from overstory competition. Stn. Note 35. Moscow ID: University of Idaho, Forestry, Wildlife and Range Experiment Station; 1979. 3 p.

Gagnon, J. D. Relationship between site index and foliage nitrogen at two crown levels for mature black spruce. For. Chron. 40: 169-174; 1964.

Gessel, S. P.; Lloyd, W. J. Effect of some physical soil properties in Douglas-fir site quality. J. For. 48: 405-410; 1950.

Gessel, S. P.; Walker, R. B.; Haddock, P. G. Preliminary report on mineral deficiencies in Douglas-fir and western redcedar. Soil Sci. Am. Proc. 15: 364-369; 1959.

Graham, R. T. Measuring annual growth rings using an electronic measuring device. Res. Note INT-289. Ogden, UT: U.S. Department of Agriculture Forest Service, Intermountain Forest and Range Experiment Station; 1980a. 13 p.

Graham, R. T. White pine vigor—a new look. Res. Pap. INT-254. Ogden UT: U.S. Department of Agriculture Forest Service, Intermountain Forest and Range Experiment Station; 1980b. 15 p.

Gysi, C.; Winget, C. H.; Bernier, B. Interactions of P, Mn, and Cu in nutrient uptake by sugar maple. Can. J. For. Res. 5: 105-108; 1975.

Hacskaylo, J.; Struthers, P. Correction of lime-induced chlorosis in pin oak. Res. Circ. 71. Wooster, OH: Ohio Agriculture Experiment Station; 1959. 5 p.

Haines, S. G.; Haines, L. W.; White, G. Nutrient composition of sycamore blades, petioles, and whole leaves. For. Sci. 25: 154-160; 1979.

Hamilton, L. S. Color standardization for foliage description in forestry. J. For. 58: 23-25; 1960.

Herring, L. J. Studies of advance subalpine fir in the Kamloops Forest District. Res. Note No. 80. Victoria, B.C.: British Columbia Forest Service; 1977. 23 p.

Herring, L. J.; Etheridge, D. E. Advance amabilis fir regeneration in the Vancouver Forest District. Joint Publ. No. 5. Victoria, B.C.: B.C. Forest Service, Canadian Forestry Service; 1976. 23 p.

Hopmans, P.; Flinn, D. W.; Aeberli, B. C. Evaluation of soil testing methods for predicting early growth and responses to phosphate fertilizer of *Pinus radiata* at Heywood, Victoria. Aust. For. Res. 8: 57-61; 1976.

Hoyle, M. C.; Mader, D. L. Relationships of foliar nutrients to growth of red pine in western Massachusetts. For. Sci. 10: 337-347; 1964.

Ike, Albert F. Symptoms of nutrient deficiency in yellow-poplar seedlings. Res. Note SE-94. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station; 1968. 4 p.

Johnson, Robert L. Natural regeneration and development of Nuttall oak and associated species. Res. Pap. SO-104. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station; 1975. 12 p.

Jones, W. W.; Embleton, T. W.; Platt, R. G. Leaf analysis and nitrogen fertilization of oranges. Citrograph 53: 367-376; 1968.

Jorgensen, J. R. Fractionation of nitrogen in three forest soils. Soil Sci. Soc. Am. Proc. 31: 707-708; 1967.

Keller, K. A.; Tregunna, E. B. Effects of exposure on water relations and photosynthesis of western hemlock in habitat forms. Can. J. For. Res. 6: 40-48; 1976.

Koenigs, J. W. Root rot and chlorosis of released and thinned western redcedar. J. For. 67: 312-315; 1969.

Krajicek, J.; Brinkman, K.; Gingrich, S. Crown competition—a measure of density. For. Sci. 7: 35-42; 1961.

Leaf, A. L. Growth of forest plantations on different soils of Finland. For. Sci. 2: 121-126; 1956.

Leaf, A. L.; Madgwick, H. A. I. Evaluation of chemical analysis of soils and plants as aids in intensive soil management. 5th World Forest Congr. Proc. 1: 554-556; 1960.

Leaphart, C. D.; Foiles, M. W. Effects of removing pole-blighted western white pine trees on growth and development of a mixed conifer stand. Res. Note INT-161. Ogden UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1972. 6 p.

Leaphart, C. D.; Grismer, M. A. Extent of roots in the forest soil mantle. J. For. 72: 358-359; 1974.

Leyton, L. The relationship between the growth and mineral composition of the foliage of Japanese larch (*Larix leptolepsis* Murr.). Plant and Soil 7: 167-177; 1956.

Leyton, L. The relationship between the growth and mineral nutrition of conifers. *In:* K. V. Thimann, ed. The physiology of forest trees. New York: Ronald Press; 1958: 323-345.

Leyton, L.; Armson, K. A. Mineral composition of the foliage in relation to the growth of Scots pine. For. Sci. 1: 210-218; 1955.

Little, E. L. Checklist of United States trees (native and naturalized). Agric. Handb. 541. Washington, DC: U.S. Department of Agriculture; 1979. 375 p.

Loach, K. Shade tolerance in tree seedlings. I. Leaf photosynthesis and respiration in plants raised under artificial shade. New. Phytol. 66: 607-621; 1967.

Lowry, G. L.; Avard, P. M. Nutrient content of black spruce needles. II. Variations with crown class and relationship to growth and yield. Woodlands Papers No. 3. Point Claire, Que.: Pulp and Paper Research Institute of Canada; 1968. 20 p.

Lowry, G. L.; Avard, P. M. Nutrient content of black spruce and jack pine needles. III. Seasonal variation and recommended sampling procedures. Woodlands Papers No. 10. Point Claire, Que.: Pulp and Paper Research Institute of Canada; 1969. 54 p.

Mader, D. L.; Thompson, B. W.; Wells, J. P. Influence of nitrogen on sugar maple decline. Bull. 582. Amherst, MA: Massachusetts Agricultural Experiment Station; 1969. 19 p.

Mayer-Krapoll, H. The use of commercial fertilizers—particularly nitrogen in forestry. Ruhr-Stickstoff Aktiengesellschaft Bochum, Germany; 1956. 111 p. [Translation by Nitrogen Division Allied Chemical and Dye Corporation, New York, NY.]

Morrison, D. J.; Johnson, A. L. S. Stump colonization and spread of *Fomes annosus* 5 years after thinning. Can. J. For. Res. 8: 177-180; 1978.

Munsell Color Company, Inc. Munsell color charts for plant tissues. Baltimore, MD: Munsell Color Co.; 1952. 22 p.

Perala, D. A.; Sucoff, E. Diagnosing potassium deficiency in American elm, silver maple, Russian olive, hackberry and box elder. For. Sci. 11: 347-352; 1965.

Phares, R. E.; Finn, R. F. Using foliage analysis to help diagnose nutrient deficiencies in black walnut. North. Nut Grow. Assoc. Annu. Rep. 62: 98-104; 1972.

Powers, R. F. Nutrient requirments of timber species: an overview. *In:* Proc. fifth Calif. forest soil fertility conf. Sacramento, CA: 1976: 7-16.

Pritchett, W. L.; Llewellyn, W. R. Response of slash pine (*Pinus elliottii* Engelm. var. *elliottii*) to phosphorus in sand soils. Soil Sci. Soc. Am. Proc. 30: 509-512; 1966.

Radwan, M. A.; DeBell, D. S. Site index, growth, and foliar chemical composition relationships in western hemlock. For. Sci. 26: 283-290; 1980.

Ralston, C. W. Evaluation of forest site productivity. *In:* Romberg, J. A.; Mikola, P. eds. Int. Rev. For. Res. 1. New York: Academic Press, 1964: 171-201.

Reisenauer, H. M. Soil and plant tissue testing in California. Sci. Bull. 1879. Berkeley, CA: University of California Division of Agriculture; 1976. 54 p.

Richards, B. N.; Bevege, D. I. Principles and practice of foliar analysis as a basis for crop-logging in pine plantations. I. Basic considerations. Plant and Soil 36: 109-119; 1972.

Sander, I. L.; Johnson, P. S.; Watt, R. F. A guide for evaluating the adequacy of oak advance reproduction. Gen. Tech. Rep. NC-23. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1976. 7 p.

Seidel, K. W. Suppressed grand fir and shasta red fir respond well to release. Res. Note. PNW-288. Portland OR: U.S. Department of Agriculture, Pacific Northwest Forest and Range Experiment Station; 1977. 7 p.

Shoulders, E.; McKee, W. H. Pine nutrition in the West Gulf Coastal Plain: a status report. Gen. Tech. Rep. SO-2. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station; 1973. 26 p.

Smith, D. M. The practice of silviculture. 7th ed. New York: John Wiley and Sons, Inc.; 1962: 33-34.

Smith, E. M. Manganese deficiency—common in maples. Am. Nurseryman. 143: 131-132; 1976.

Sprague, H. B. Hunger signs in crops. New York: David McKay Company, Inc.; 1964: 359-361.

Stage, Albert R. Prognosis model for stand development. Res. Pap. INT-137. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1973. 32 p.

Stage, A. R. An expression for the effect of aspect, slope, and habitat type on tree growth. For. Sci. 22: 457-460; 1976.

Steele, R.; Arno, S. F.; Pfister, R. D. Preliminary forest habitat types of the Nezperce National Forest. Boise, ID: U.S. Department of Agriculture, Intermountain Forest and Range Experiment Station; 1976. 71 p. Review draft.

Steinback, K. Growth responses of clonal lines of American sycammore growth under different intensities of nutrition. Can. J. Bot. 49: 353-358; 1971.

Steinbrenner, E. C. Forest soil productivity relationships. *In:* Forest soils of the Douglas-fir region. Pullman, WA: Washington State University Cooperative Extension Service; 1979: 199-229.

Stone, E. L.; Taylor, A.; Richards, N. A.; DeMent, J. Soil and species adaptation: red pine plantations in New York. N. Am. For. Soils Conf. Proc. 1: 181-184; 1958.

Switzer, G. L.; Nelson, L. E. Nutrient accumulation and cycling in loblolly pine (*Pinus taeda* L.) plantation ecosystems: the first twenty years. Soil Sci. Soc. Am. Proc. 36: 143-147; 1972.

Switzer, G. L.; Nelson, L. E.; Smith, W. H. The mineral cycle in forest stands. *In:* Forest fertilization-theory and practice. Muscle Shoals, AL: Tennessee Valley Authority; 1968: 1-9.

Tarrant, R. F.; Isaac, L. A.; Chandler, R. F., Jr. Observations on litter fall and foliage nutrient content of some Pacific Northwest tree species. J. For. 49: 914-915; 1951.

Tucker, G. F.; Emmingham, W. H. Morphological changes in leaves of residual western hemlock after clear and shelterwood cuttings. For. Sci. 23: 195-203; 1977.

Ulrich, A. Physiological bases for assessing the nutritional requirements of plants. Annu. Rev. Plant Physiol. 3: 207-228; 1952.

U.S. Department of Agriculture, Forest Service. Forest fertilization symposium proceedings. Gen. Tech. Rep. NE-3. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1973. 245 p.

van den Burg, J. Naaldverkleuringen bij enige Picea-soorten: oorzaken en bestrijding door bemesting. Nederlands Bosbouw Tijdschrift. 51(10): 223-230; 1979. [English summary.]

Walker, R. B.; Gessel, S. P.; Haddock, P. G. Greenhouse studies in mineral requirements of conifers: western redcedar. For. Sci. 1: 51-60; 1955.

Wallis, G. W.; Morrison, D. J. Root rot and stem decay following commercial thinning in western hemlock and guidelines for reducing losses. For. Chron. 51: 203-207; 1975.

Waring, R. H.; Youngberg, C. T. Evaluating forest sites for potential growth response of trees to fertilizer. Northwest Sci. 46: 67-75; 1972.

Wells, C. G.; Metz, L. G. Variation in nutrient content of loblolly pine needles with season, age, soil and position on the crown. Soil Sci. Soc. Am. Proc. 27: 90-93; 1963.

Wellner, C. A. Estimating light intensity beneath coniferous forest canopies: simple field method. Res. Note INT-250. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1979. 3 p.

White, E. H.; Leaf, A. L. Soil and tree potassium contents related to tree growth. I. H NO_3-EXTRAC. soil K. Soil Sci. 98: 395-402; 1964.

White, E. H.; Leaf, A. L. Soil and tree potassium contents related to tree growth. II. Tissue K as determined by total tree analysis techniques. Soil Sci. 99: 109-114; 1965.

White, D. P. Variation in the nitrogen, phosphorus, and potassium contents of pine needles with season, crown position, and sample treatment. Soil Sci. Soc. Am. Proc. 18: 326-330; 1954.

White, D. P.; Wright, J. W. Pigment changes in Scotch pine (*Pinus sylvestris* L.) induced by controlled environment. Paper of the Michigan Academy of Science Arts and Letters No. 52. East Lansing, MI: Michigan Agricultural Experiment Station; 1966: 55-62.

Woods, David B.; Turner, Neil C. Stomatal response to changing light by four tree species of varying shade tolerance. New. Phytol. 70: 77-84; 1971.

Zinke, P. J. The pattern of individual forest trees on soil properties. Ecology. 43: 130-133; 1962.

Graham, Russell T. Influence of tree and site factors on western redcedar's response to release: a modeling analysis. Res. Pap. INT-296. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1982. 19 p.

Fifteen western redcedar stands were sampled to determine the magnitude and duration of growth response to release treatments. Site factors such as slope and aspect were related to the growth response, as were tree characteristics such as age and diameter at breast height. In addition both foliage characteristics and soil characteristics were related to the growth response.

KEYWORDS: diameter increment, foliar elements, diameter regression model, soil elements

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